Urban Sewage Delivery Heat Transfer System (2): Heat Transfer Forms and Efficiency Analysis[1]

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Abstract: The thimble delivery heat-transfer (TDHT) system is one of the primary modes to utilize the energy of urban sewage. Using the efficiency-number of transfer units method ($\varepsilon - NTU$), the heat-transfer efficiencies of the parallel-flow and reverse-flow TDTH forms are analyzed and the calculation formulas and characteristic are also given. The results indicate that the efficiency of the parallel-flow form is greater than that of the reverse-flow, so the TDTH system must choose the parallel-flow form. The distance-load ratio (DLR) is defined and the minimum DLR is obtained by the technical and economic feasibility analysis. The paper will provide references for heat-transfer calculation and schematic determination of urban sewage cool or heat source applied delivery heat transfer methods.

Key words: urban sewage; delivery heat transfer; efficiency; parallel-flow; reverse-flow.

1. INTRODUTION

As the former said, urban sewage thimble delivery heat transfer system has two heat transfer form: parallel-flow and reverse-flow， as the former chart one showing, when intermediary water and sewage entering from the two ends of the same thimble, forming reverse-flow heat-transfer form, otherwise is parallel-flow heat-transfer form. Generally speaking， the efficiency of reverse-flow heat-transfer form is larger than it of parallel-flow form, so generic heat transfer adopts reverse-flow form or near it, but in the application of urban sewage transfer heat transfer means, it is not routinism. Toward urban sewage cool or heat source double pass TDTH system, how to calculate the thermal efficiency of parallel-flow and reverse-flow, what is the largest of heat-transfer efficiency, what is the change of sewage temperature and the quantity of supplying heat, what heat-transfer form is adopted in project assign, and so on, these questions must be solved when scheme is ascertained and system is calculated and designed. Moreover, although the TDTH system of urban sewage makes full use of sewage transfer space to progress heat-transfer, this transfer space doesn't always satisfy the need of heat-transfer, namely how much of the heating air-conditioning burthen need how much of the transfer length. Quite distinctness, if burthen is larger and the transfer is finite, TDTH system can not be adopted. Thus it is necessary to determine the relation of load and transfer distance. The thesis makes use Efficiency-Number of Transfer Units method ($\varepsilon - NTU$) to analyze the heat-transfer efficiency of double pass thimble delivery heat-transfer system, presenting efficiency calculate formula, variety characteristic ,max and so on, defining the concept of distance-load ratio (DLR), and the smallest DLR of technology economic viability can't be obtained by analyzing.

2. HEAT TRANSFER EFFICIENCY

The thesis adopts $\varepsilon - NTU$ means of literature [1] to analyze heat-transfer efficiency and the quantity of heat-transfer. Generally, the heat-transfer efficiency (ε) of transfer is defined that the ratio between difference in temperature of small thermal capacity

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liquid imports and exports and difference in temperature of cold and heat liquid imports, namely $\varepsilon = \left| \dfrac{t_{\min 1} - t_{\min 2}}{t_{\max 1} - t_{\min 1}} \right|$. If ε is larger, the change in temperature of small thermal capacity liquid is larger, and the quantity of heat is larger too, therefore what is called heat-transfer efficiency is higher.

NTU is namely *Number of Transfer Units,* $NTU = KA/C_{\min}$, $C_{\min}$ is the smaller of heat transfer liquid thermal capacity. Through analysis of above flow resistance and energy cost, we know that the economy flux ratio Cr of transfer heat-transfer means is between 0.54 and 0.85, namely sewage flux is smaller, and $C_{\min} = \rho V_w c_w$. It is necessary to point out that though depending on the definition of literature [1]: the ratio between the difference in temperature of large thermal capacity liquid imports and exports and difference in temperature of cold and heat liquid imports is not the meanings of heat-transfer efficiency. The math relation between corresponding ε and NTU is still exact, even ε is larger and the quantity of heat-transfer is larger, illuminating whether the quantity of mediate water is larger or the quantity of sewage is larger. This thesis calculate depends on sewage temperature and flux ($\varepsilon = \Delta t_w / \Delta t_1$, $NTU = KA/C_w$, $Cr = C_w / C_z$), formula and conclusion are both correct .In experiment we test that the difference between surface' sewage density and specific heat and cleaning water is much smaller, in this paper they are considered equal, namely thermal capacity ratio is equal to flux ratio. In urban sewage heat-transfer system, convection thermo resistance and dirt thermo resistance occupy largish proportion, therefore the coefficient of heat transmission K of system is very stable, and basically don't change with the clear water current velocity. For concrete project, the temperature of dirty water import (t_{w1}) is certain. The temperature of mediate water of import (t_{z1}) is decided by the evaporator export of the heat pump machine set, and variety is quite small. This is to say the difference between dirty water and mediate water of import $\Delta t_1 = t_{w1} - t_{z1}$ is a basically certain value. According to the definition style of heat-transfer efficiency ε , we know toward adverse current single pass thimble heat-transfer : $\varepsilon_{1n} = \dfrac{t_{w1} - t_{w2}}{t_{w1} - t_{z1}}, \varepsilon_{2n} = \dfrac{t_{w2} - t_{w3}}{t_{w2} - t_{z2}}$. Due to the NTU of going and returning two pass thimble are same, so $\varepsilon_{1n} = \varepsilon_{2n}$, even $\left(t_{w1} - t_{w2}\right) Cr = t_{z2} - t_{z1}$, finally we can get overall efficiency of contranatant two pass thimble:

$$\varepsilon_N = \frac{t_{w1} - t_{w3}}{t_{w1} - t_{z1}} = 2\varepsilon_{1n} - \left(1 + Cr\right)\varepsilon_{1n}^2 \qquad (1)$$

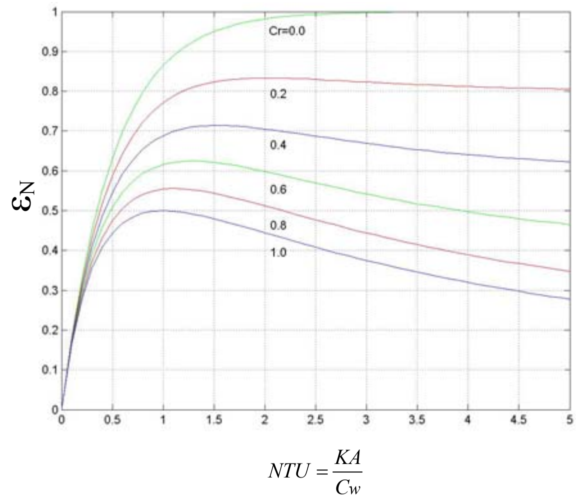

Fig.1 Reverse-flow heat efficiency of TDHTS

Contranatant single pass heat-transfer efficiency:

$$\varepsilon_{1n} = \frac{1 - \exp\left(-NTU(1 - Cr)\right)}{1 - Cr \cdot \exp\left(-NTU(1 - Cr)\right)}$$

Put it to (1), we can get:

$$\varepsilon_N = \frac{\left(1 - Cr\right)\left[1 - \exp\left(-2NTU(1 - Cr)\right)\right]}{\left[1 - Cr \cdot \exp\left(-NTU(1 - Cr)\right)\right]^2} \qquad (2)$$

Specially, if $Cr = 1$, we have that:

$$\varepsilon_N = \frac{2NTU}{(1 + NTU)^2} \qquad (3)$$

The relation curve between ε_N, Cr and single pass

NTU as figure 1 show:

As the same pass, we can get parallel-flow single pass thimble heat- transfer

$\varepsilon_{1S}=\frac{t_{w1}-t_{w2}}{t_{w1}-t_{z2}}$, $\varepsilon_{2S}=\frac{t_{w2}-t_{w3}}{t_{w2}-t_{z1}}$, even $\varepsilon_{1S}=\varepsilon_{2S}$, $\left(t_{w1}-t_{w2}\right)Cr=t_{z3}-t_{z2}$, finally getting the overall efficiency of two pass thimble parallel-flow:

$$\varepsilon_S=\frac{t_{w1}-t_{w3}}{t_{w1}-t_{z1}}=\frac{2\varepsilon_{1s}-\left(1+Cr\right)\varepsilon_{1s}^2}{1-Cr\varepsilon_{1s}^2} \quad (4)$$

Heat-transfer efficiency of parallel-flow single pass: and $\varepsilon_{1S}=\frac{1-\exp\left(-NTU(1+Cr)\right)}{1+Cr}$, put it to (4)

$$\varepsilon_S=\frac{\left(1+Cr\right)\left[1-\exp\left(-2NTU(1+Cr)\right)\right]}{1+Cr+Cr^2+2Cr\cdot\exp\left(-NTU(1+Cr)\right)-Cr\cdot\exp\left(-2NTU(1+Cr)\right)} \quad (5)$$

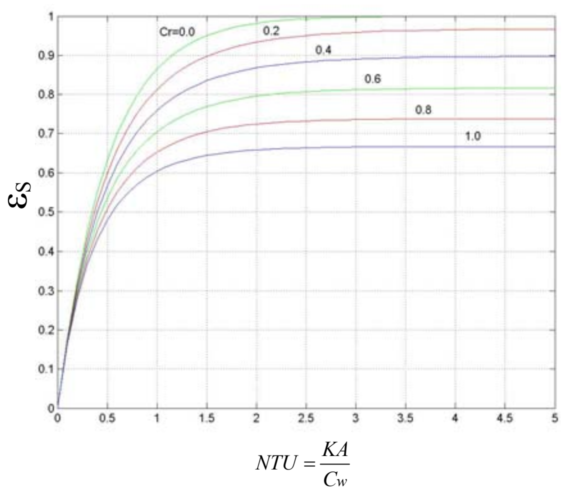

Fig.2 Parallel-flow heat efficiency of TDHTS

In Fig.2 the relation curve between ε_S , Cr and single pass NTU as figure 2 is shown. After exchanging heat through thimble, the export temperature of sewage t_{w3} and the quantity of heat-transfer Q_e are decided by heat-transfer overall efficiency ε_N , ε_S of two pass thimble. For example, the quantity of heat-transfer in the case of parallel-flow:

$$Q_e=\rho c_w V_w \varepsilon_S \Delta t_1 \quad (6)$$

All NTU in above formula (2),(3),(5) adopt the NTU of single pass thimble.

3. CONTRASTIVE ANALYSIS

Through formula (1), we know that the overall efficiency of reverse-flow heat-transfer is the efficiency of single pass quadratic function, if having $\varepsilon_{1n}=\frac{1}{1+Cr}$, we can get $\varepsilon_{N\max}=\frac{1}{1+Cr}$. It is to say that toward the system of reverse-flow two pass thimble heat-transfer, it is not always better if the heat-transfer area A is larger, when A is excessive large and tend to infinitude, the heat-transfer efficiency will be reduced and tend to be $1-Cr$. In fig.1, the curve of $\varepsilon-NTU$ has peak value also indicates that explains this point. It is widely divergent compared with the opinion of general transfer, the cause of this phenomenon have two aspects:

(1) If improving heat-transfer area A (NTU), the efficiency ε_{1n} of first pass thimble heat-transfer, the lower temperature of sewage ($t_{w1}-t_{w2}$) and elevated temperature of intermediary water $(t_{z2}-t_{z1})$ all will be improved, but leading to the export temperature t_{w2} be lower, t_{z2} to be higher. In this pass, the available difference in temperature ($t_{w2}-t_{z2}$) of the second pass thimble is very small, and quantity of heat is smaller, accordingly, reducing the overall quantity of heat-transfer and the efficiency of

heat-transfer.

(2) Continue to improve the area A of heat transfer unto what is larger than a certain value, reverse-flow two pass thimble heat transfer will appear the phenomenon of returning heat, namely in the first pass, sewage sends quantity of heat to intermediary water; In the second pass, intermediary water also sends part of heat to sewage. This part of heat energy that linger between thimbles occupancy the two pass heat-transfer area, improving single pass heat-transfer efficiency but reducing the synthesis efficiency of two pass. Such as in the case of $Cr = 1$ and $A \to \infty$, the quantity of heat between sewage sends to intermediary water and intermediary water sends to sewage to be equal, the system's overall efficiency $\varepsilon_N = 0$.

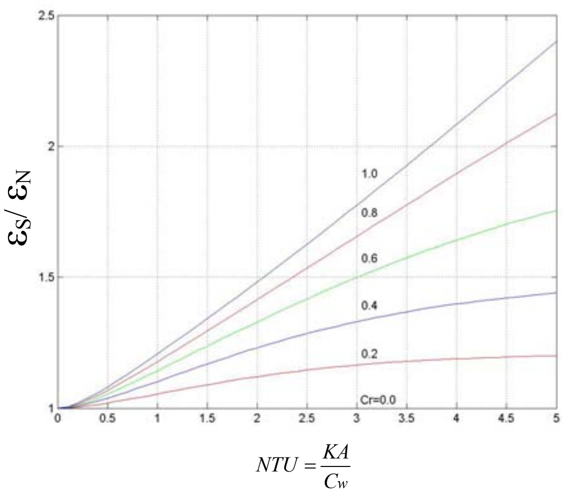

Fig.3 The efficiency ratio of double-pass TDHTS

It is known that from formula (5), it is natural the overall efficiency of parallel-flow two pass thimble's system is the monotony increasing function of NTU. Because of $\varepsilon_{1S} < \frac{1}{1+Cr}$, the max value of parallel-flow two pass's overall efficiency is $\varepsilon_{S\max} = \frac{1+Cr}{1+Cr+Cr^2}$, certainly arriving at the condition of the most efficiency that heat-transfer area A is infinite.

Two pass thimble parallel-flow heat transfers don't exist with "return heat" phenomenon.

Although in the same conditions of NTU, the single pass efficiency of reverse-flow is larger than that in parallel-flow, but from formula (1), (4), it is known that the two pass overall efficiency of reverse-flow is not larger than parallel-flow. Through mathematical analysis and numerical calculations, it is easily to see $\varepsilon_S / \varepsilon_N \geq 1$ is constant tenable, and the ratio of NTU is increasing monotonous function .Partial results are shown in figure 3, for example, $Cr = 1$, $NTU = 2$, ε_S is 1.5 times of ε_N. The two pass thimble heat-transfer system's efficiency of parallel-flow is larger than reverse-flow. It is widely divergent compared with the opinion of general transfer. The reason is the reverse-flow form to take full advantage of the difference in temperature of each trip (particularly single-pass), but wasting most of the heat-transfer area. The parallel-flow form don't make full use of the difference in temperature of each trip, but making full use of the whole system's heat-transfer area. Based on the above, the urban sewage double pass thimble heat-transfer's system should adopt parallel-flow form.

4. ANALYSIS OF PARALLEL-FLOW

Although only when $NTU \to \infty$, the heat-transfer efficiency of parallel-flow system gets the maximum value $\varepsilon_{S\max} = \frac{1+Cr}{1+Cr+Cr^2}$

If NTU is greater, the role to increase ε_S is smaller. As figure 4 shows, as $NTU > 1.3 \sim 1.8$, $\varepsilon_S / \varepsilon_{S\max} \geq 0.95$ and $NTU > 1.6 \sim 2.2$, it is $\varepsilon_S / \varepsilon_{S\max} \geq 0.97$.

This character should be fully utilized in the system's design and can not be blind pursuit of higher efficiency and increased thimble length, investment and operating costs.

Because formula (5) is too complex, it is not easy used in project applications. Taylor launched their rank, and adopting the first three napes, we get the below formula.

$$\varepsilon_S' = \left(\frac{1+Cr}{1+Cr+Cr^2}\right)\left(1-\frac{2Cr}{1+Cr+Cr^2}e^{-NTU(1+Cr)}-\frac{1-Cr+Cr^2}{1+Cr+Cr^2}e^{-2NTU(1+Cr)}\right) \quad (7)$$

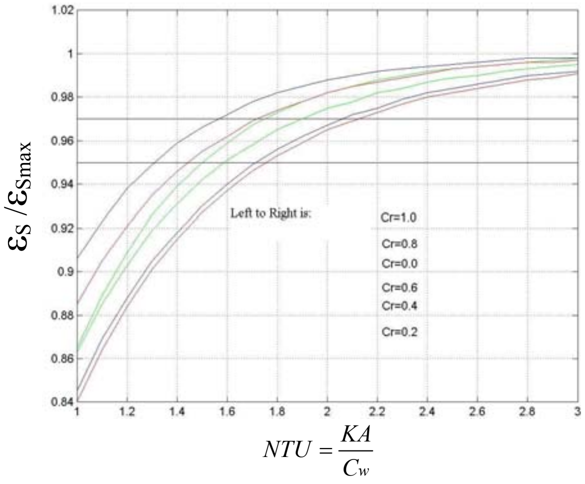

Fig.4 The efficiency ratio of parallel-flow TDHTS

The result error is all within $\pm 3\%$, so this form can easily be applied in engineering design.

5. THE MINIMAL DLR VALUE

The thimble delivery heat-transfer method of urban sewage cool and heat sources generally using symmetrical double pass form, single pass wasting investment and operating costs, four or more pass trenches or peak pip's construction is too much difficult. For specific projects, the cold and heat load Q_d is ascertained and unchanged, reducing the length of thimble can be seen to save investment, but reducing heat-change efficiency, resulting in the volume of sewage 's augment, it will increase operating costs and internal and external diameters, and bringing many technical difficult problems. How to determine the length of thimble will be an economic optimization. Ordering the heat-transfer loss factor

$$\beta = \frac{\varepsilon_{S\max} - \varepsilon_S}{\varepsilon_{S\max}} \quad (8)$$

According to (7), having

$$\beta = \frac{2Cr}{1+Cr+Cr^2}e^{-NTU(1+Cr)} + \frac{1-Cr+Cr^2}{1+Cr+Cr^2}e^{-2NTU(1+Cr)}$$

Dispel quadratic equation

$$NTU = \ln\left(\frac{1-Cr+Cr^2}{\sqrt{(1+\beta)Cr^2+\beta(1+Cr^4)}-Cr}\right)\frac{1}{(1+Cr)} \quad (9)$$

And

$$NTU = \frac{KA}{C_{\min}} = \frac{K\pi d_1 L}{\rho c_w V_w}$$

Order $\Delta t_1 = t_{w1} - t_{z1}$.

We have $V_w = \dfrac{Q_d}{\rho c_w (1-\beta)\varepsilon_{S\max}\Delta t_1}$. Also since

$d_1 = \sqrt{\dfrac{4V_w}{\pi u_w}}$, So finally we get

$$DLR = \frac{L}{\sqrt{Q_d}} = G(\beta, Cr)\sqrt{\frac{\rho c_w u_w}{4\pi\Delta t_1 K^2}} \quad (10)$$

In below formula

$$G(\beta, Cr) = \ln\left(\frac{1-Cr+Cr^2}{\sqrt{(1+\beta)Cr^2+\beta(1+Cr^4)}-Cr}\right)\sqrt{\frac{1+Cr+Cr^2}{(1-\beta)(1+Cr)^3}}$$

$L/\sqrt{Q_d}$ in the formula (10) is defined of the ratio of distance load, namely DLR (Distance-Load *Ratio*), L is the half-thimble's long, commonly it is the distance between buildings and trunk sewer. If the design adopts the economic flow ratio Cr and speed ratio Ur which are determined in the former, and the sewage flow u_w, import temperature difference Δt_1, integrated heat transfer coefficient K is basically unchanged from, Therefore ,we know the total operating costs of the sewage can be expressed as :

$$F_w = Af_w(\beta) \quad (11)$$

A is a constant in the formula, it is related with the five invariables

$$f_w(\beta) = \ln\left(\frac{1-Cr+Cr^2}{\sqrt{(1+\beta)Cr^2+\beta(1+Cr^4)}-Cr}\right)(1-\beta)^{-0.85}$$

The relation of $f_w(\beta)$ and β that is as figure 5 showing. The curve of $Cr = 0.6$ is readily found in the almost coincide with the $Cr = 1$, namely $f_w(\beta)$ is affected by parameter flux smaller than Cr. But in the range of $0 < \beta \le 0.25$, increased β plays a

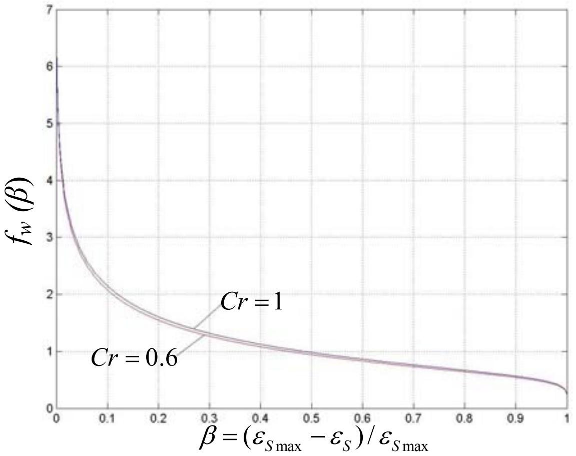

Fig.5 Relation between economics and β

great role in reducing sewage total operating costs .When $\beta > 0.25$, continue to increase β to reduce operating costs much less than its role in the study, it will bring water to increase investment is increasing, design deformities, steel tubes, pumps models difficulties, the construction can not be carried out and a series of economic and technological problems. There is only a conclusion through theoretical analysis from pumps operating costs, taking into account various factors in actually works, the $0.05 \le \beta \le 0.25$ is feasible in the economy and technology.

Taking into account the economic flux ratio $0.54 \le Cr \le 0.85$, economic heat-transfer loss factor $\beta : 0.05 \le \beta \le 0.25$, the general velocity of flow of sewage around $u_w = 2.5m/s$, import temperature difference $\Delta t_1 = 10^0C$, the total heat transfer coefficient stability around $K = 750W/(m^2\,{}^0C)$, the DLR of thimble transfer heat-transfer as table.1.

Clearly, the value of minimum distance load ratio DLR which is technology feasible, reasonable economic in urban sewage thimble delivery heat-transfer method applied is about 8.8. If a project's DLR value greater than 8.8, it has satisfied the technical and economic conditions necessary condition of thimble heat transfer method.

6. CONCLUTIONS

Through the above analysis, this article gains the following important conclusions：

1) Adopting $\varepsilon - NTU$ law, we get the heat-transfer efficiency formula of two-pass thimble system's parallel-flow and reverse-flow, finding the heat-transfer efficiency of reverse-flow's TDHT system is not be along with heat-transfer area 's augment and don't appear the abnormal phenomenon of monotonous increasing, through analyzing the phenomenon we see it is aroused by the factor of "return heat" and so on.

2) Given the parallel-flow and reverse-flow heat-transfer efficiency formula, comparing and analyzing the parallel-flow and reverse-flow TDHT system efficiency, we find in double pass TDHT systems, the efficiency of parallel-flow always larger than reverse-flow anomaly, analyzing the causes of the phenomenon. TDHT on urban sewage system must adopt the form of parallel-flow rather than reverse-flow.

3) The maximum efficiency of parallel-flow TDHT system is $\varepsilon_{S\max} = \dfrac{1+Cr}{1+Cr+Cr^2}$, When $NTU = 2$, the system efficiency has reached the 97% of maximum efficiency heat. Presenting a

Tab.1 The technical and economical DLR of TDTH system ($m/kW^{0.5}$)

β \ Cr	0.54	0.60	0.65	0.70	0.75	0.80	0.85
0.05	19.346	19.166	18.970	18.763	18.549	18.331	18.110
0.10	14.788	14.761	14.538	14.393	14.240	14.080	13.916
0.15	12.266	12.177	12.075	11.961	11.838	11.710	11.576
0.20	10.549	10.478	10.394	10.299	10.196	10.088	9.974
0.25	9.259	9.200	9.128	9.047	8.959	8.864	8.766

Note: The data in the table corresponding to the single-pass length L m unit, the unit load Q for the reception is kW

simple engineering calculations and analysis which are suited to the two-pass parallel-flow TDHT efficiency formula, as detailed in Type (7).

4) Through technical and economic optimization analysis that double pass TDHT system heat loss factor (β)scope should be $0.05 \le \beta \le 0.25$, and on basis the urban sewage thimble heat transfer method can be applied technically feasible, reasonable economic smallest distance load ratio DLR is about 8.8.

This thesis will provide a theoretical reference in scheme identify and heat-transfer calculation of the double pass TDHT urban sewage systems.

REFERENCES

[1] Ximin Zhang, Zepei Ren. Heat Transfer (Vol.4)[M]. Beijing: China Architecture Industry Press, 2001,278-280.(In Chinese)

[2] Ronghua Wu, Dexing Sun. The flowing resistance and heat transfer characteristic of urban sewage [J]. Heating Ventilation & Air Conditioning, 2005, 35（2）:54-56.(In Chinese)

[3] Funamizu N, Iisa M． Reuse of heat energy in wastewater implementation examples in Japan. Water Science and Technology， 2001,43(10): 277-286.

[4] Dexing Sun, Ronghua Wu. The application method of delivery heat transfer of urban sewage cool and heat source [P]. P.R. China Patent: 200510009836.9,2005. (In Chinese)

[5] Arashi, Norio. Evaluation of energy use in district heating and cooling plant using sewage and one using air as heat source. Journal of the Japan Institute of Energy , 2000, (5): 446-454

[6] Yoshii T. Technology for utilizing unused low temperature difference energy. Journal of the Japan Institute of Energy, 2001, (8): 696-706.

[7] Stijemstrom B. Feeding large heating pumps form sewage water treatment plants.Proceedings of the International Conference on Applications and Efficiency of Heat Pump Systems, 1991,Oct 1: 183-192.

[8] Ronghua Wu, Dexing Sun. Characteristic of operating parameters of urban sewage source heat-pump [J]. Fluid Machinery, 2005,33（12）:46-52. (In Chinese)